Back to the Future: Greenland's Contribution to Sea level Change

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ABSTRACT

The Greenland Ice Sheet is presently making a significant contribution to global sea level rise. Predictions for the future suggest that this will continue and likely accelerate further during the remainder of this century. However, a comprehensive understanding of ongoing mass balance flux has only become possible in the last decade or so following the development of satellite and other new observational technologies. As a result, it is not clear whether the patterns observed today are typical of the past or not. In this paper I review predictions for Greenland's contribution to future sea level rise and then place these estimates in the context of the evidence for past change during the 20th century, the last few millennia and the Eemian interglacial. There is evidence that the ice sheet responds sensitively to changes in conditions in the adjacent North Atlantic, leading to a hypothesis that annual and decadal fluctuations in Atlantic air and sea surface temperatures shape the ice sheet's contribution to global sea level change. The recent loss of ice needs also to be seen in the context of an overall increase in ice sheet size, and the related advance of the ice sheet margin by tens of kilometres during the last few millennia. I conclude by arguing that in order to better constrain the role of the Greenland Ice Sheet in future sea level, improvements in our understanding of present day change of the ice sheet must be matched by equal strides in understanding how the ice sheet has evolved in the past.

INTRODUCTION

The Greenland Ice Sheet shares centre stage with the Antarctic Ice Sheet in current debates about the nature and impacts of global warming. Data suggest that rising northern hemisphere temperatures are causing accelerated ice sheet melting and according to recently published data collected by the Gravity Recovery and Climate Experiment (GRACE), the Greenland Ice Sheet has contributed ~15-30% of the global sea level rise since 2003. Several studies (discussed below) suggest that the Greenland Ice Sheet is capable of contributing >0.5 m of global sea level rise by the end of this century, with potentially profound social and economic consequences.

But the new data behind such predictions cover only a relatively short time interval, often less than a decade or so and in the case of GRACE, only since 2002. Short time series such as these need interpreting with caution, since deep boreholes through the ice sheet show that patterns of mass accumulation vary significantly over space and time (e.g. Andersen et al., 2006). Because of this variability it is important that recent trends in ice sheet mass balance are considered in a longer-term context. Although each successive year of observation generates ever more data, the only way to provide meaningful decadal to century-scale perspectives on Greenland's behaviour is to look to the past. We can estimate temperature changes from weather stations for much of the twentieth century (e.g. Chylek et al., 2004),and compute mass balance of the ice sheet from 1958 to 2007 (Rignot et al., 2008) and the surface mass balance back to 1866 (Wake et al., 2009). However, consideration of earlier changes requires examination of proxy records of ice sheet behaviour drawn from ice cores, glacial geomorphology and other palaeoclimate archives from Greenland and its adjoining seas.

In this paper I start by reviewing future predictions Greenland's contribution to global sea level as a result of climate change. I then provide a context for these predictions, reviewing evidence for ice volume change during the past before reflecting on the challenges of linking observations and reconstructions of ice sheet history and contribution to sea level.

FUTURE SCENARIOS

The IPCC Fourth Assessment Report (IPCC, 2007) predicts that the Greenland Ice Sheet will make a relatively modest contribution to sea level rise in the next 100 years. Using different low to high emission scenarios, Greenland is estimated to contribute between 0.01 and 0.12 m of global sea level rise by 2099, out of a total of between 0.18 to 0.59 m (5 to 95% range, based on the interval between 1980-1999 and 2090-2099). Thermal expansion of the world's oceans is predicted to be by far the largest contributor to future sea level rise, accounting for 0.1 to 0.41 m of sea level rise by the end of this century. The IPCC recognises that Greenland's contribution (and that of Antarctica) may be an underestimate, since at the time of its writing quantitative estimates of the potential dynamic contribution of the ice sheet through accelerated discharge via its outlets could not be made with confidence. More recent research has sought to quantify what this dynamic contribution could be under high but physically plausible scenarios of ice flux. Using this approach, Pfeffer et al. (2008) conclude that Greenland could contribute between 0.16 and 0.54 m to global sea level rise by AD 2100. When the approach is also applied to Antarctica and other ice caps and glaciers, the combined projection of high, but plausible, sea level rise by AD 2100 lies between 0.78 and 2.08 m, including the effects of thermal expansion of the oceans.

How reasonable is it to hypothesise that global sea level might rise several meters within a century, and that the Greenland Ice Sheet might contribute >0.5 m to that rise? Some support for such high rates of sea level rise is forthcoming from a recent study of sea level changes during the last (Eemian, Marine Isotope Stage 5e) interglacial, c. 120,000 years ago. At their maximum, global mean temperatures then were comparable to those predicted in the coming century and sea level was several meters higher than present, most likely because much of the Greenland Ice Sheet had melted (Cuffey and Marshall, 2000). Using a Red Sea stable oxygen isotope record from planktonic foraminifera, Rohling et al. (2008) reconstructed average rates of sea level rise of up to 1.6 m per century during this interglacial. These rates are for periods when sea level was higher than present and are therefore not associated with large glacial-interglacial fluctuations in ice volume. Rohling et al. (2008) did not attribute the source of these large oscillations in sea level but they note that rates as high as this would melt the equivalent of the Greenland Ice Sheet in approximately four centuries. There are some important caveats to this work; the height uncertainties are rather large (each sample point has a one sigma height uncertainty of 6 m), the Red Sea cores used are only partly dated, and the high rates of sea level variability reported are not fully replicated between the two cores studied. Moreover, equivalent meter-scale fluctuations in sea level are not recorded in the later part of the current interglacial, suggesting a mode of ice sheet dynamic hitherto not seen in the Holocene. Nevertheless, if valid, the research of Rholing et al. (2008) suggests that rapid rates of sea level rise are possible in the future, especially for conditions when sea level is higher than present, although an implication of the Pfeffer et al. (2008) study is that on its own Greenland would only ever be able to contribute about a third of the 1.6 m rise per century proposed, and probably less given the reduced size of the ice sheet at this time.

So, it is plausible that the Greenland Ice Sheet might contribute >0.5 m of global sea level rise in the next century and some believe that such high rates of global sea level rise have occurred in the past. Such a rise would require a sustained high flux of ice over the entire coming century. However, as we shall now see, there is considerable evidence from the past to show that the mass balance of the Greenland Ice Sheet fluctuates on a decadal basis, experiencing phases of positive and negative mass balance that change broadly in tune with variations in air and sea surface temperatures over Greenland and the neighbouring North Atlantic.

GREENLAND CONTRIBUTION TO 20TH CENTURY SEA LEVEL

Tide gauge and satellite observations show that global sea level has risen over the 20th century but that the rate of rise has not been constant. Thus, Cazenave et al. (2008) estimate that global sea level rise between January 1993 and February 2008 was 3.1±0.1 mm yr (Figure 1) which compares with an average rate during the last 50 years of c. 1.7 mm yr (Church and White, 2006; Holgate, 2007). Estimates of Greenland's changing mass during the last decade obtained from remotely sensed data vary widely but all suggest the ice sheet today is making a positive contribution. Initial observations suggested that peripheral thinning of the ice sheet was offset by thickening above 2000 m (Krabill et al., 1997; Thomas et al., 2006) such that the overall sea level contribution was negligible (Zwally et al., 2005). However, more recent observations by the GRACE satellites show significant mass loss from the higher parts of the ice sheet as well, due to longer and more intense melt seasons, especially in 2007 (Wouters et al., 2008, Figure 2).

The cause of this mass loss seems clear: rising temperatures are causing increased melting. For example, summer temperatures have risen by an average of 1.7ºC over the southern part of Greenland between 1991-2006 and this has lengthened the melt season (Hanna et al., 2008). Many outlet glaciers here and elsewhere in Greenland have accelerated their speed (Rignot and Kanagaratnam, 2006; Luckman et al., 2006; Howat et al., 2008) and many coastal glaciers have also thinned significantly (Thomas et al., 2006). Water generated by greater surface melt may percolate to the bed of the ice sheet and reduce basal friction, causing the rate of flow of the glaciers to speed up (Zwally et al., 2002) although the importance of this process is debated (Joughin et al., 2008). Moreover, warm ocean currents penetrating fjords are also associated with increased melting of glaciers and ice streams with marine termini (Holland et al., 2008; Hanna et al., in press). But the broader implications of some of these recent changes for the long-term decadal to century-scale ice sheet stability is uncertain. In the last few years several of the retreating glaciers have slowed or even started to readvance (Howat et al., 2007). Moreover, Nick et al. (2009) use a numerical model to demonstrate that tidewater outlet glaciers are very sensitive to changes in their terminus boundary conditions and adjust dynamically very quickly to short-term climate fluctuations. They warn that recent dynamic instabilities in the Helheim Glacier in southeast Greenland, and potentially elsewhere, do not provide a reliable basis for long-term prediction of ice sheet mass balance change.

The recent loss of mass from Greenland means it is now making an increasingly positive contribution to global sea level rise. Estimates from GRACE since 2002 vary between 100-270 Gt/yr which is equivalent to a sea level rise of between ~0.4 to 0.7 mm yr (Velicogna and Wahr, 2006; Ramillien et al., 2006; Chen et al., 2006; Luthcke et al., 2006; Wouters et al., 2008). The variability in these estimates reflects differences in the time period of observation, different data sources, different methods used in data analysis, and also real spatial and temporal variations in ice sheet volume. Cazenave et al. (2008) concluded that since 2003 the rate of global sea level rise fell from 3.1±0.1 to 2.5 ± 0.5 mm yr largely due to reduced thermal expansion of the oceans. The recent GRACE estimates referred to above show that Greenland is presently contributing between c. 15-30% of global sea level rise, well above the estimates made by the IPCC.

A longer-term 20th century perspective is provided by modelling experiments that accurately account for vertical changes in both the sea surface and the sea floor when ice sheets gain or lose mass. Thus, Mitrovica et al. (2001) analysed spatial trends in rates of tide gauge measured sea level for 23 selected sites. They observed that rates of 20th century sea level rise in European sites were lower than the global average and concluded that this sea level "fingerprint" is compatible with a Greenland contribution to global sea level of ~0.6 mm yr during the 20th century. This estimate is within the range cited above from the GRACE studies of recent Greenland contribution to global sea level rise (~0.4 to 0.7 mm yr). Resolving the ongoing spatial pattern of sea level fingerprints is likely to be complex, not least due to non-uniform variations in thermal expansion. Nevertheless, this important analysis suggests a persistent and significant positive Greenland contribution to global sea level during the 20th century.

Greenland and the North Atlantic

The Greenland Ice Sheet owes much of its existence to the large moisture source provided by the adjacent North Atlantic and, although the ice sheet responds to variations in a variety of forcing factors, including volcanic activity as well as variations in solar output (e.g. Hanna et al., 2005), it is no surprise to find that the ice sheet is sensitive to changes in atmospheric and oceanographic conditions in the North Atlantic region. This sensitivity is illustrated below by considering how the climate over Greenland responds to fluctuations in the North Atlantic Oscillation (NAO) and the Atlantic Multi-decadal Oscillation (AMO). The mechanisms that cause fluctuations in these indicies are not certain although it seems probable that they respond in part at least to the non-linear dynamics of the extratropical atmosphere and variations in the strength of the thermohaline circulation (Hurrell et al., 2001; Sutton and Hodson, 2005). Neither is presently predictable to any significant degree and, for example, a return to cooler conditions over Greenland in future decades might be expected if their previous pattern of variability continues into the future.

The NOA describes a redistribution of atmospheric mass between the Arctic and the subtropical Atlantic. Variations in NAO phase generate large changes in surface air temperature, winds, storminess and precipitation over the Atlantic, and also influence the oceans by causing changes in heat content, gyre circulations, salinity, high latitude deep water formation and sea ice cover (Hurrell et al., 2001). There is no agreed method for defining the NAO, although one measure is provided by the varying sea level pressure between the Icelandic low and the Azores sub-tropical high pressure system (Figure 3). The NAO is positive when the Icelandic low is deep, causing enhanced westerly air flow across the North Atlantic with cold and dry conditions over Greenland. A shift to a weaker or negative NAO (associated with a weaker Icelandic low) sees warmer conditions and higher precipitation over Greenland. Higher air temperatures over Greenland since the early 1990s (Hanna et al., 2008), as well as the penetration of warmer ocean currents into the fjords of south Greenland since the mid 1990s (Holland et al., 2008) are compatible with the gradual shift from a positive to a more negative NAO that has occurred since the mid 1980s (Box et al., 2002; Hanna et al., 2008) (Figure 3).

Further evidence of the close link between conditions in the North Atlantic and across the Greenland Ice Sheet is provided by the Atlantic Multi-decadal Oscillation (AMO). The AMO describes a 65 to 75 yr variation (0.4ºC range) in North Atlantic sea surface temperatures (SSTs). Expressed as deviations from the 1961-1990 mean, the AMO is characterised by warm (1930 to 1960) and cool (1905-1925 and 1970-1990) SST phases. The AMO returned to more positive values again in the 1990s (Figure 4a). There is widespread evidence that changes in the AMO are related to multi-decadal variations in a range of climate records, including Atlantic hurricanes and North American and European summer climate (e.g. Knight et al., 2006).

Temperature records from coastal stations in Greenland show that the recent increase in temperatures is not unprecedented in the last century and that an earlier episode of warmer than average temperatures is likely linked to changes in the AMO. Thus, Chylek et al. (2006) conclude that the rate of warming in Greenland between 1930-1940 was c. 50% higher than that observed between 1995-2005 (Figure 4b). Both warm phases broadly coincide with periods when the AMO shifted from a cooler to a warmer phase. These climate fluctuations almost certainly impacted the mass balance of the ice sheet. A recently published mass balance history for the ice sheet extending back to 1958 reconstructs mass deficit during the warm 1960s (110±70 Gt/yr), near balance in the cool 1970s-1980s (30±50 Gt/yr) and accelerated loss since the 1990s (up to 267±38 Gt/yr in 2007) (Rignot et al., 2008). These estimates are in broad agreement with reconstructed trends in surface mass balance by Hanna et al. (2005). Wake et al. (2009) identify a distinct change from positive to negative surface mass balance anomalies during the pronounced warming that began in the 1920s and continued until about 1960. They conclude that the surface mass balance changes between 1995 and 2005 are not exceptional within the past 140 years.

Is there any proven link between these ice mass fluctuations in Greenland, temperatures and changes in the rate of 20th century global sea level? Although the overall trend in 20th century sea level was upwards, there have been periods of faster and slower rates of change. The two decades showing the fastest increase in global sea level are centred on 1980 (+5.31 mm yr) and 1939 (+4.68 mm yr), while lowest rates of change are centred on 1964 (-1.49 mm yr) and 1987 (-1.38 mm yr) (Holgate, 2007). Woodworth et al. (2008) reviewed possible links between periods of accelerated and reduced rates of global sea level rise and variations in the NAO, AMO and a range of other climate indicators that include the Pacific Decadal Oscillation, Arctic Oscillation and the Southern Oscillation Index. They concluded that many of these indicies change in phase with the major variations in the rate of global sea level rise. In terms of Greenland's contribution to these sea level fluctuations, the warmth of the 1980s and the cool period of the 1960s coincide with changes in ice sheet mass balance identified by Rignot et al. (2008). Moreover, the change modelled by Wake et al. (2009) in the 1920s coincides with the acceleration in global sea level noted above at this time by Holgate (2007) and Woodworth et al. (2008), although the Wake et al. (2009) analysis did not include potential variations in ice sheet dynamic contributions and estimates for outlet glacier discharge in their study.. Given the above, it is reasonable to propose that decadal variations in the mass balance of the Greenland Ice Sheet were, in part at least, responsible for variations in the rate of global sea level rise during the 20th century.

GREENLAND CONTRIBUTION TO SEA LEVEL DURING THE LAST FEW MILLENNIA

Neoglacial ice sheet growth

The "neoglacial" extends from about 4000 years ago to the end of the Little Ice Age (LIA) and is characterised by a shift to cooler conditions. According to temperature profiles from the Dye 3 and GRIP ice cores, this was equivalent to a 2ºC fall in average air temperatures over the centre of the ice sheet between 4000 and 2000 years ago, with further cool periods at c. AD 1500 and AD 1750 (Dahl-Jensen et al., 1998). There is geomorphological and sea level evidence from Greenland to suggest that the ice sheet margin advanced over the duration of the neoglacial (Kelly, 1980; Weidick, 1993; Van Tatenhove et al., 1996; Long et al., in press). This evidence includes reworked organic material ripped up from former tundra surfaces by advancing ice, reworked late Holocene marine faunas in recent moraines adjacent to tidewater glaciers, as well as a rise in relative sea level in west and south Greenland driven, in part at least, by renewed ice loading during the late Holocene (Kelly, 1980).

Reconstructing the magnitude and timing of the neoglacial advance is difficult because a growing ice sheet destroys former ice limits. Ice sheet models provide the best means of estimating ice volume changes, especially when they are constrained by sea level and other geomorphological evidence referred to above. Current models suggest that despite the 50-100 km advance of the ice sheet margin, especially in west Greenland where it was most pronounced, the neoglacial regrowth of the ice sheet caused a relatively small draw-down of global sea level, amounting to <0.2 m (Tarasov and Peltier, 2002; Fleming and Lambeck, 2004; Simpson et al., in press). This is equivalent to a rate of sea level fall of c. 0.05 mm yr when averaged over the last 4000 years.

In reality, it is likely that regrowth of the ice sheet and its associated impact on global sea level varied through time. The most pronounced periods of neoglacial cooling recorded in the ice cores occurred between 4000-2000 BP, AD 1000-1500 and about AD 1850 (Dahl-Jensen et al., 1998). If we assume that these cooler intervals coincided with ice sheet expansion, then these are the periods that Greenland is most likely to have slowed global sea level rise. Conversely, warmer conditions identified by Dahl-Jensen et al. (1998) occur between 0-1000 AD, AD 1500-1750 and after AD 1850 and it is reasonable to hypothesise that these intervals were associated with positive global sea level contributions. Beyond Greenland, there is no evidence for coherent variations in the rate of sea level change during the late Holocene that can be unambiguously attributed to variations in the neoglacial volume of the Greenland Ice Sheet, although an acceleration during the last 100-150 years seems widespread and may have a Greenland origin (e.g. Gehrels et al., 2008).

The record from the last few thousand years shows that the Greenland Ice Sheet has experienced a significant increase in mass during the cooler conditions of the "neoglacial". All around the margins of the present ice sheet are fresh moraines that mark the maximum position of this advance, reached at the end of the Little Ice Age (the late 19th or early 20th century). Most of these lie within a few kilometers of the present ice sheet margin and show that in the recent past the ice sheet was more extensive than present. Although retreat is obvious in many areas, in west Greenland there remains a considerable distance between the present ice margin and its position at the start of the neoglacial, when model experiments suggest that the margin lay many tens of kilometers inland of its present position (e.g. Simpson et al., in press).

CONCLUSIONS

Future predictions suggest that the Greenland Ice Sheet could contribute >0.5 m of global sea level rise by the end of this century and one sensitivity study predicts that rates of mass loss would match those last seen as far back as c. 10,000 years ago, at the time of fastest ice sheet retreat (Pfeffer et al., 2008). Satellite and field observations show that the evolving mass of the Greenland Ice Sheet is making an increasingly positive contribution to global sea level rise and although estimates vary, GRACE data indicate this contribution is between 0.4 and 0.7 mm yr, equal to c. 15-30% of the total global rise in sea level measured since 2003. The present contribution is considerably larger than predicted by the Fourth IPCC Assessment Report but is less than some high-end estimates of sea level rise from Greenland in the next century (e.g. Pfeffer et al., 2008) and the range of high rates of sea level rise reconstructed from the last interglacial (Rholing et al., 2008).

The improved spatial and temporal resolution of recent geodetic methods means that we are gaining new and unprecedented insights into the dynamics of the ice sheet, its glaciers and ice streams. These observations are rapidly changing our understanding of how Greenland responds to climate change. There is, for example, growing evidence that the surface mass balance and glacier dynamics in Greenland are related to changes in air and ocean temperatures that vary in phase with changing conditions in the adjacent North Atlantic. Two periods of rapid atmospheric warming in the 20th Century, one in the 1980s and the other in the 1920s, coincide with phase shifts in the AMO and likely saw Greenland making a positive contribution to accelerations in the rate of global sea level rise recorded by tide gauge records. But advances in monitoring current change must be matched by the development of new understanding regarding the past behaviour of the ice sheet. We still know very little regarding the mass balance history of the ice sheet during the last few centuries, despite the large climate changes that existing records suggest have occurred. Future research must bridge the gap between geological reconstructions and recent direct observations if we are to establish firm decadal and century-scale trends in ice sheet mass balance and hence determine whether the variations we observe today are within or beyond normal ice sheet variability. Only then will we reduce the considerable uncertainty that presently exists regarding the contribution of the Greenland Ice Sheet to past and future sea level change.

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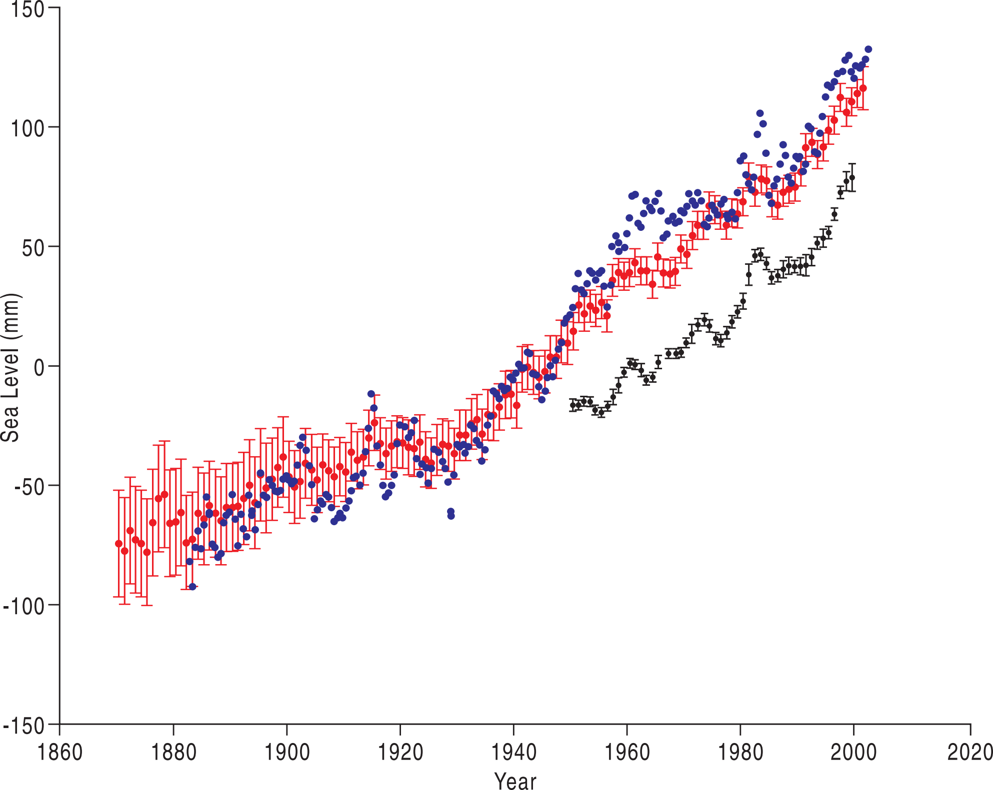
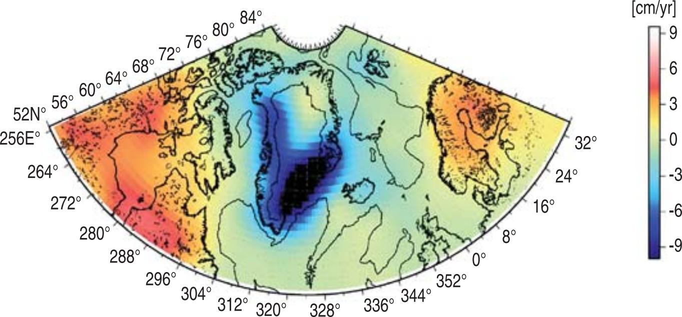
List of Figures

Cover photograph caption

Icebergs in Kangia (Jakobshavn Isfjord) close to the town of Ilulisaat, West Greenland. These icebergs mostly originate from the calving terminus of Jakobshavn Isbrae which collapsed catastrophically in the late 1990s. Many scientists believe this collapse was driven by warmer air and / or sea surface temperatures. See “Back to the future: Greenland’s contribution to sea level change” by A. J. Long (p. x-x)..



150
100
50
0
-50
-100
-150
Sea Level (mm)
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year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9
6
3
0
-3
-6
-9
52N°
56°
60°
64°
68°
72°
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80°
84°
256E°
264°
272°
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304°
312°
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352°
0°
8°
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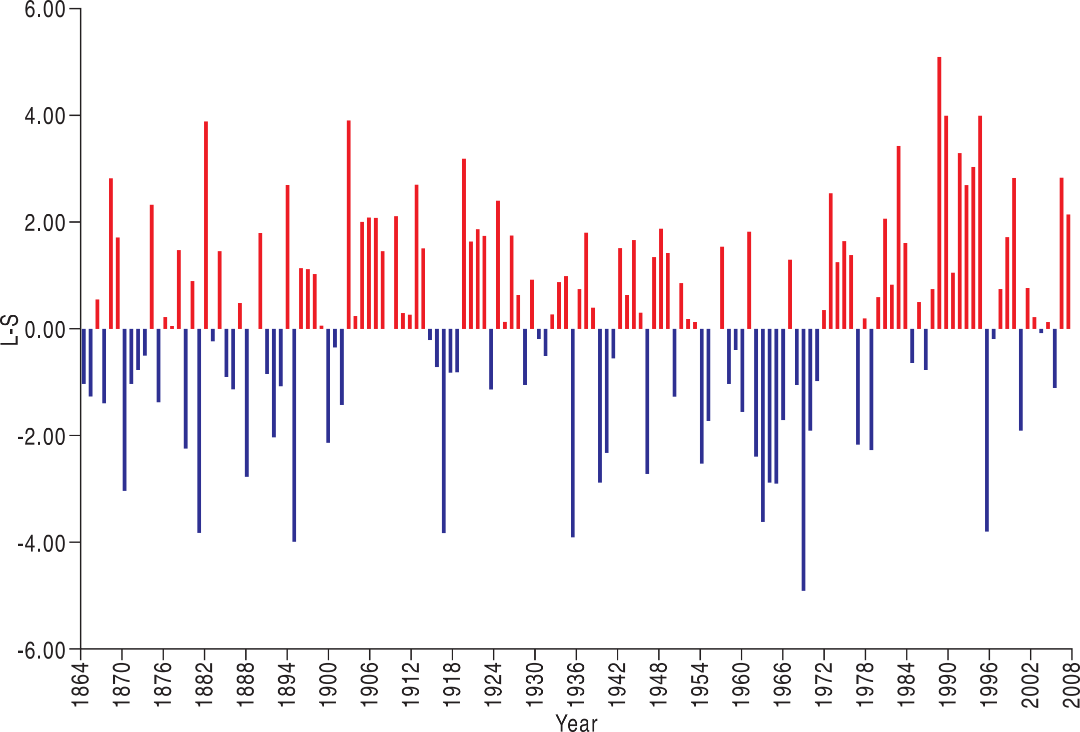

6.00
4.00
2.00
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-2.00
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L-S
1864
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1894
1900
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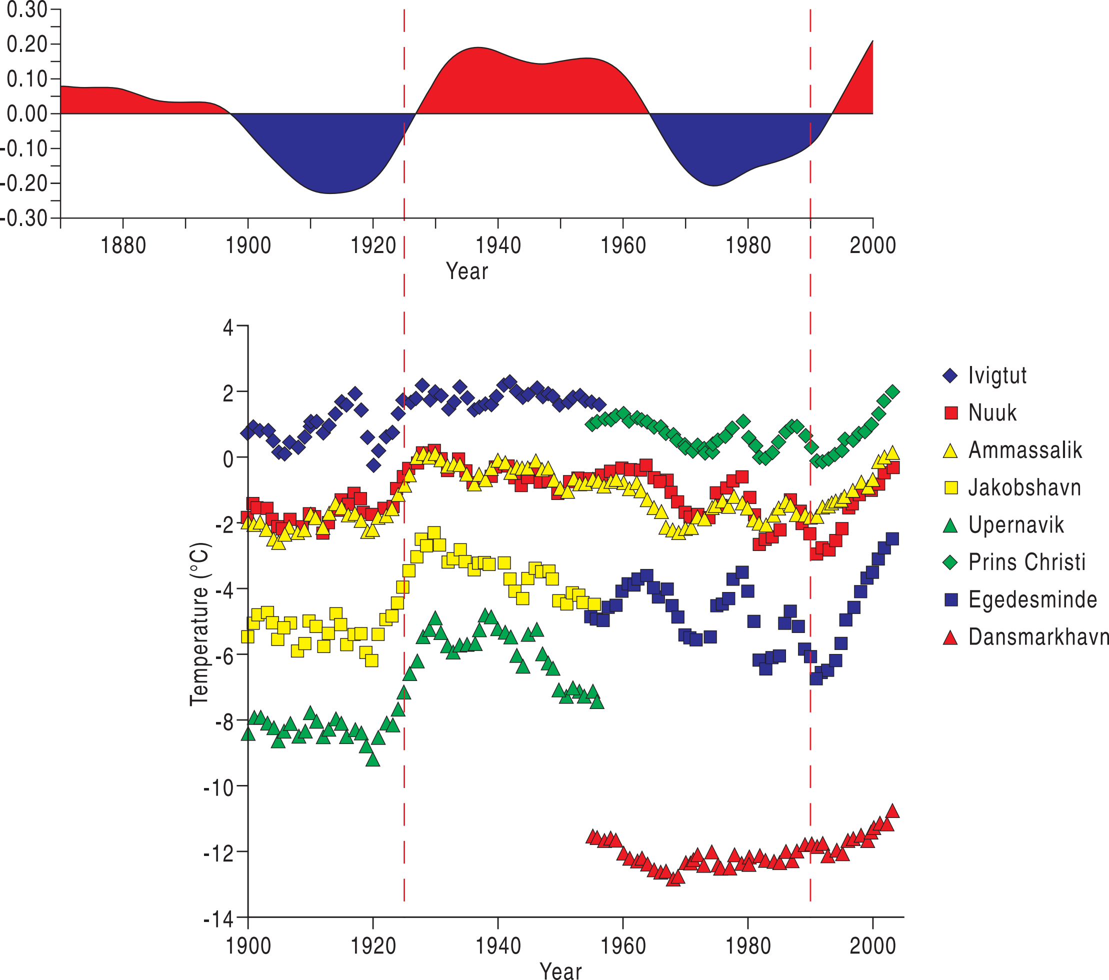
2002
2008
Year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0.20
0.10
0.00
-0.10
-0.20
-0.30
1880
1900
1920
1940
1960
1980
2000
Year
4
2
0
-2
-4
-6
-8
-10
-12
-14
Temperature (°C)
1900
1920
1940
1960
1980
2000
Year
Ivigtut
Nuuk
Ammassalik
Jakobshavn
Upernavik
Prins Christi
Egedesminde
Dansmarkhavn